

On resonance search in dijet events at the LHC

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New strategy for resonance search in dijet events at the LHC is discussed. The main distribution used for a bump search is the dijet invariant mass distribution with appropriated cuts. The crucial cut, which is applied to maximize signal significance, is on (pseudo)rapidity difference between the two jets. This is due to the exponential growing of the QCD background contribution with this variable. Usually it is assumed that signal from almost all exotic models populates the central dijet rapidity region $y_{1,2} \simeq 0$ and $|y_1 - y_2| \simeq 0$. By contrast, the excited bosons do not contribute into this region, but produce an excess of dijet events over the almost flat QCD background in $\chi = \exp|y_1 - y_2|$ away from this region. Therefore, different sets of cuts should be applied for new physics search depending on the searched resonance properties. In order to confirm the bump and reveal the resonance nature various angular distributions should be used in addition. In particular, for the excited bosons the special choice of parameters could lead to a dip in the centrality ratio distribution over the dijet invariant mass instead of a bump, expected in the most exotic models.

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I. INTRODUCTION

Due to the largest cross section of all processes at the hadron colliders dijet production opens a possibility to search for a signal, s , of new physics in the very early data. In particular, a bump in the dijet invariant mass distribution would indicate the presence of a resonance decaying into two energetic partons. However, due to the huge QCD background, b , it is necessary to optimize signal significance ratio, s/\sqrt{b} , in order to enhance the bump.

The distribution of dijets over the polar angle θ , being angle between the axis of the jet pair and the beam direction in the dijet rest frame, is directly sensitive to the dynamics of the underlying process. While the QCD processes are dominated by t -channel gluon exchanges, which lead to a Rutherford-like distribution $1/(1 - \cos\theta)^2$, exotic physics processes proceed mainly through the s -channel, where the spins of the resonance and of the initial and final parton states uniquely define the angular distributions.

The absolute value of the dijet rapidity difference is related to the polar scattering angle θ with respect to the beam axis by $\Delta y \equiv |y_1 - y_2| = \ln[(1 + |\cos\theta|)/(1 - |\cos\theta|)] \geq 0$. Therefore, the QCD background contribution on this variable is dominated by the exponential growing factor $\exp(\Delta y)$ from the Rutherford scattering. The choice of the other variable $\chi \equiv \exp(\Delta y) = (1 + |\cos\theta|)/(1 - |\cos\theta|) \geq 1$ is motivated by the fact that Rutherford scattering does not depend on it and the QCD distribution is almost flat.

In the next section we will consider a model independent signal distributions of new physics from resonances up to spin of one and corresponding Δy cut optimizations for signal significance. Present analysis is based on a study of dijet mass angular distributions [1], which has

been shown to play important role in disentangling of the resonance properties revealing the unique signature of the excited bosons.

II. A UNIQUE SIGNAL OF EXCITED BOSONS

Let us consider different possibilities for the spin of a resonance and its possible interactions with partons. The simplest case of the resonance production of a (pseudo)scalar particle h with spin 0 in s -channel leads to a uniform decay distribution on the scattering angle

$$\frac{d\Gamma_0(h \rightarrow q\bar{q})}{d\cos\theta} \propto |d_{00}^0|^2 \sim 1. \quad (1)$$

The spin-1/2 fermion resonance, like an excited quark q^* , leads to asymmetric decay distributions for the given spin parton configurations

$$\frac{d\Gamma_{1/2}(q^* \rightarrow qg)}{d\cos\theta} \propto |d_{1/2,1/2}^{1/2}|^2 \sim 1 + \cos\theta \quad (2)$$

and

$$\frac{d\Gamma_{1/2}(q^* \rightarrow qg)}{d\cos\theta} \propto |d_{1/2,-1/2}^{1/2}|^2 \sim 1 - \cos\theta. \quad (3)$$

However, the choice of the variables, which depend on the absolute value of $\cos\theta$, cancels out the apparent dependence on $\cos\theta$. In other words, the distributions (2) and (3) for dijet events look like uniform distributions (1).

According to the simple formula

$$\frac{d\Gamma}{d\Delta y} = \frac{d\cos\theta}{d\Delta y} \frac{d\Gamma}{d\cos\theta}, \quad (4)$$

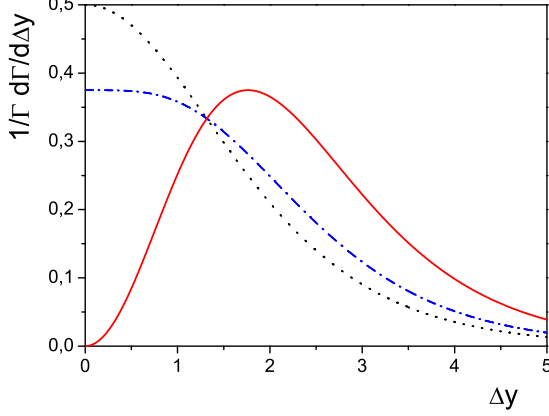


FIG. 1: The normalized angular dijet distributions as functions of Δy for the scalar (or/and spin-1/2), the gauge bosons with the minimal couplings and the excited bosons are shown with the dotted, dash-dotted and solid curves, respectively.

the uniform distribution leads to kinematical peaks at $\Delta y = 0$ (the dotted curve in Fig. 1)

$$\frac{1}{\Gamma_0} \frac{d\Gamma_0}{d\Delta y} = \frac{2e^{\Delta y}}{(e^{\Delta y} + 1)^2}. \quad (5)$$

According to [1, 2] there are only two different cases for the spin-1 resonances depending on their interactions with light fermions.

Usually the gauge bosons Z' , W' and axigluons have minimal gauge interactions with the known light fermions

$$\mathcal{L}_{Z'} = \sum_f \left(g_{LL}^f \bar{\psi}_L^f \gamma^\mu \psi_L^f + g_{RR}^f \bar{\psi}_R^f \gamma^\mu \psi_R^f \right) Z'_\mu, \quad (6)$$

which preserve the fermion chiralities and possess maximal helicities $\lambda = \pm 1$. At a isospin-symmetric pp collider, like the LHC, such interactions lead to the specific symmetric angular distribution of the resonance decay products over the polar angle θ ,

$$\frac{d\Gamma_1(Z' \rightarrow q\bar{q})}{d\cos\theta} \propto |d_{11}^1|^2 + |d_{-11}^1|^2 \sim 1 + \cos^2\theta. \quad (7)$$

Similar to the uniform distribution, eq. (7) also leads to kinematical peaks at $\Delta y = 0$ (the dash-dotted curve in Fig. 1)

$$\frac{1}{\Gamma'_1} \frac{d\Gamma'_1}{d\Delta y} = \frac{3e^{\Delta y}(e^{2\Delta y} + 1)}{(e^{\Delta y} + 1)^4}. \quad (8)$$

Another possibility is the resonance production and decay of new longitudinal spin-1 bosons with helicity $\lambda = 0$. The new gauge bosons with such properties arise in many extensions [2] of the Standard Model (SM), which solve the Hierarchy Problem. They transform as doublets ($Z^* W^*$) under the fundamental representation of the SM

$SU(2)_W$ group like the SM Higgs boson and, therefore, have not minimal gauge interactions with the known light fermions.

While the Z' bosons with helicities $\lambda = \pm 1$ are produced in left(right)-handed quark and right(left)-handed antiquark fusion, the longitudinal Z^* bosons are produced through the anomalous chiral couplings with the ordinary light fermions

$$\mathcal{L}_{Z^*} = \sum_f \frac{g_{RL}^f}{M} \bar{\psi}_R^f \sigma^{\mu\nu} \psi_L^f \partial_{[\mu} Z_{\nu]}^* + \text{h.c.} \quad (9)$$

in left-handed or right-handed quark-antiquark fusion [3]. The anomalous interactions (9) are generated on the level of the quantum loop corrections and can be considered as effective interactions. The gauge doublets, coupled to the tensor quark currents, are some types of “excited” states as far as the only orbital angular momentum with $\ell = 1$ contributes to the total angular momentum, while the total spin of the system is zero. This property manifests itself in their derivative couplings to fermions and a different chiral structure of the interactions in contrast to the minimal gauge interactions (6).

The anomalous couplings lead to a different angular distribution of the resonance decay

$$\frac{d\Gamma_1(Z^* \rightarrow q\bar{q})}{d\cos\theta} \propto |d_{00}^1|^2 \sim \cos^2\theta \quad (10)$$

than the previously considered ones. At first sight, the small difference between the distributions (7) and (10) seems unimportant. However, the absence of the constant term in the latter case results in novel experimental signatures.

A striking feature of the distribution (10) is the forbidden decay direction perpendicular to the boost of the excited boson in the rest frame of the latter (the Collins–Soper frame [4]). It leads to a profound dip at $\cos\theta = 0$ in the Collins–Soper frame [3] in comparison with the scalar and gauge boson distributions. The same dips present also at $\Delta y = 0$ [5] (the solid curve in Fig. 1)

$$\frac{1}{\Gamma_1^*} \frac{d\Gamma_1^*}{d\Delta y} = \frac{6e^{\Delta y}(e^{\Delta y} - 1)^2}{(e^{\Delta y} + 1)^4}. \quad (11)$$

It can be seen from Fig. 1 that the excited bosons have unique signature in the angular distributions. They manifest themselves through the absolute minimum at $\Delta y = 0$ and absolute maximum at $\Delta y = \ln(3 + \sqrt{8}) \approx 1.76$.

III. SELECTION CUT OPTIMIZATIONS

From Fig. 1 one can be seen that all signal distributions decrease at $\Delta y \rightarrow \infty$, while the QCD background increases exponentially with Δy (as discussed in the Introduction). Therefore, applying the cut $\Delta y < a$ (i.e. considering dijet events with $\Delta y < a$ only) one can enhance the signal significance, $\mathcal{S} = s/\sqrt{b}$, choosing the maximum of the corresponding distribution.

So, we can define the relative signal significance as the ratio of the integrals of the normalized signal distributions (5), (8), (11) to the QCD background distribution

$$\mathcal{S}(a) = \frac{\int_0^a \frac{1}{\Gamma} \frac{d\Gamma}{d\Delta y} d\Delta y}{\int_0^a \exp(\Delta y) d\Delta y}. \quad (12)$$

Then the significance for the isotropic distribution

$$\mathcal{S}_0(a) = \frac{\sqrt{e^a - 1}}{e^a + 1} \quad (13)$$

reaches the maximum at $a = \ln 3 \approx 1.10$ (the dotted curve in Fig. 2).

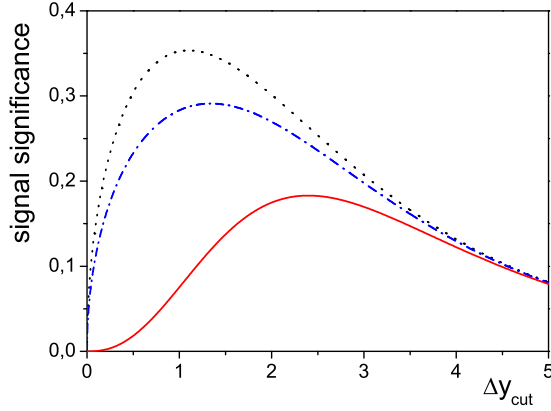


FIG. 2: The relative signal significance distributions as functions of the cut parameter a for the scalar (or/and spin-1/2), the gauge bosons with the minimal couplings and the excited bosons are shown with the dotted, dash-dotted and solid curves, respectively.

The gauge bosons with the minimal coupling (6) possess almost similar distribution as the scalar and spin-1/2 particles (the dash-dotted curve in Fig. 2)

$$\mathcal{S}'_1(a) = \frac{(e^{2a} + e^a + 1) \sqrt{e^a - 1}}{(e^a + 1)^3} \quad (14)$$

with the maximum at $a = \ln(4 + \sqrt[3]{764 + 36\sqrt{401}}/2 + 20/\sqrt[3]{764 + 36\sqrt{401}}) - \ln 3 \approx 1.34$.

These numbers coincide with the selection cut $a = 1.3$ applied by the CMS [6] and ATLAS [7] collaborations for the resonance search in dijet events. However, it is obviously not optimal for the excited bosons search due to very different shape of the angular distribution.

Indeed, direct expression of the signal significance function for the excited bosons

$$\mathcal{S}_1^*(a) = \frac{(e^a - 1)^2 \sqrt{e^a - 1}}{(e^a + 1)^3} \quad (15)$$

lead to the maximum at $a = \ln 11 \approx 2.40$ (the solid curve in Fig. 2). Therefore, application of the usually accepted

cut at $a = 1.3$ drastically reduces the number of signal events from the excited bosons. In other words, there are no model independent cuts for the resonance search with different spin properties.

Since the peak of the excited boson distribution is shifted from the origin (Fig. 1), one can expect that applying a more sophisticated cut $b < \Delta y < a$ the absolute maximum of the signal significance function of the two variables

$$\mathcal{S}_1^*(a, b) = \frac{\left(\frac{e^a - 1}{e^a + 1}\right)^3 - \left(\frac{e^b - 1}{e^b + 1}\right)^3}{\sqrt{e^a - e^b}} \quad (16)$$

can be found. Precise solution of this problem leads to the following values of the parameters $a = \ln(6 + \sqrt{21}) \approx 2.36$ and $b = \ln(6 - \sqrt{21}) \approx 0.35$ at the maximum. However, an impact of this solution is expressed in 1.3% gain in comparison with the maximum of the expression (15).

In order to confirm the event excess in the invariant dijet mass distribution one can use the various ratios of angular distributions (see [1]). They do not only allow to discover a resonance but also to reveal its properties. In [7] new observable

$$F_\chi = \frac{N(\Delta y < b)}{N(\Delta y < a)}, \quad (b < a) \quad (17)$$

has been introduced, as the fraction of dijet events produced centrally versus the events number in more wide region for a specified dijet mass range. It has been used for quark contact interaction search at the following parameter values $a = 3.4$ and $b = 1.2$. Here we will show that the same observable with appropriated parameters can be used for a resonance search as well.

For example, in the case of the isotropic distribution one can maximize the deviation from the QCD ratio $F_\chi^{\text{QCD}} = N_{\text{QCD}}^{(b)} / N_{\text{QCD}}^{(a)}$

$$\begin{aligned} F_\chi^0(a, b) &= \frac{N_{\text{QCD}}^{(b)} + N_{\text{new}}^{(b)}}{N_{\text{QCD}}^{(a)} + N_{\text{new}}^{(a)}} \\ &\approx F_\chi^{\text{QCD}} \left(1 + \frac{N_{\text{new}}^{(b)}}{N_{\text{QCD}}^{(b)}} - \frac{N_{\text{new}}^{(a)}}{N_{\text{QCD}}^{(a)}} \right) \\ &\equiv F_\chi^{\text{QCD}} + \delta F_\chi^0 > F_\chi^{\text{QCD}}. \end{aligned} \quad (18)$$

Since $N_{\text{QCD}}^{(a)} \propto e^a - 1$ and $N_{\text{new}}^{(a)} \propto (e^a - 1)/(e^a + 1)$ the absolute maximum appears at $a = \log(2 + \sqrt{5}) \approx 1.44$ and $b = \log(\sqrt{5}) \approx 0.80$.

For the spin-1 resonances the expressions $N_{\text{new}}^{(a)}$ are more complicated and solutions cannot be expressed through radicals. So, for the gauge bosons with the minimal interactions $N_{\text{new}}^{(a)} \propto (e^{3a} - 1)/(e^a + 1)^3$ and the absolute maximum is reached at $a \approx 1.63$ and $b \approx 0.94$. For the both considered cases there are only positive contributions to F_χ from the new physics and F_χ is always greater than F_χ^{QCD} .

By contrast to this, the excited bosons represent more interesting case with absolute minimum and maximum at $a \approx 1.07$, $b \approx 0.57$ and $a \approx 3.10$, $b \approx 2.25$, correspondingly (Fig. 3), due to a peculiar shape of the angular

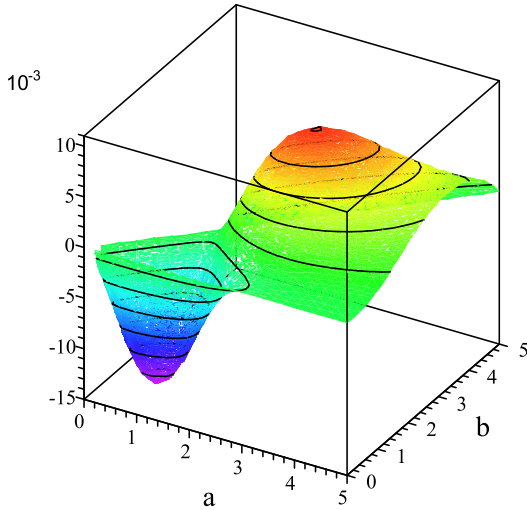


FIG. 3: The F_{χ}^{*1} shape for the excited bosons.

distribution $N_{\text{new}}^{(a)} \propto (e^a - 1)^3 / (e^a + 1)^3$.

IV. DISCUSSIONS AND COMPARISONS

Since the scalar resonances peak at origin more stronger than spin-1 gauge bosons with the minimal couplings and the maximum of the excited bosons distribution is shifted away from the origin, they have decreasing relative signal sensitivities at their maxima

$$\mathcal{S}_0|_{\text{max}} : \mathcal{S}'_1|_{\text{max}} : \mathcal{S}^*_1|_{\text{max}} \simeq 1.2 : 1.0 : 0.6. \quad (19)$$

Here we assume the same production cross section for all resonances. Moreover, if the selection cut $\Delta y < 1.3$ is applied for the case of the excited bosons search, it reduces 1.6 times the sensitivity than the optimal cut $\Delta y < 2.4$. For example, if a some insignificant 2σ excess is observed for the commonly accepted cut, it could become an evidence for the optimal cut in the excited bosons case.

In order to obtain absolute signal significances for some models we have used the CalcHEP package [8]. Let us compare two models [5] for the charged spin-1 resonances W' and W^* with mass of 1 TeV, which have the same production cross sections at the LHC in the leading order approximation. The signal events and QCD background have been generated with MRST2007lomod PDFs at 7 TeV center-of-mass energy and the following jet cuts: $M_{jj} > 700$ GeV and $|\eta_j| < 2.5$.

In order to optimize search the additional selection cut $\Delta y < 1.3$ has been applied in the case of W' resonances and $\Delta y < 2.4$ for the W^* case. So, already 100 pb^{-1} is enough to obtain 5σ signal significance in the first case and 230 pb^{-1} for the second case. If we have applied $\Delta y < 1.3$ cut for the excited boson W^* , 560 pb^{-1} will be necessary to reach the same sensitivity.

It should be stressed also, that the ratio F_{χ} is less affected by the systematic errors. However, the impact of new physics from the different resonances to F_{χ} occurs as

$$\delta F_{\chi}^0|_{\text{max}} : \delta F_{\chi}^{'1}|_{\text{max}} : \delta F_{\chi}^{*1}|_{\text{min}} \simeq 1.4 : 1.0 : -0.4. \quad (20)$$

Therefore, the contribution of spin-1 resonances and mainly the excited bosons are more suppressed than in (19). Nevertheless, for the excited bosons a unique possibility exists that the absolute minimum and maximum are present. In these cases we have $F_{\chi}^{*1}|_{\text{min}} < F_{\chi}^{\text{QCD}}$ and $F_{\chi}^{*1}|_{\text{max}} > F_{\chi}^{\text{QCD}}$, correspondingly. Although the absolute minimum is 1.3 times dipper than the maximum value, more wider regions in the later case lead to smaller uncertainties. It will allow to verified once again the excited bosons signature.

In conclusion we would like to note that in this paper we have considered the novel optimization of angular cuts aimed at the most effective search for the new resonances with different angular distributions of their decay products. Simple analytical formulas have been obtained. Even for the same resonance spin there are different optimized cuts with respect to the resonance interactions.

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